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CAINOZOIC STRATIGRAPHY AND STRUCTURE OF THE MALLEE REGION, VICTORIA

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Abstract

The Tertiary history of the Mallee Region is intimately related to the migration within the Murray Basin of Eocene to Pliocene seas and rivers over a terrain of subdued to near-planar topography bevelling Cambrian-?basal Ordovician, Permian, and Lower Cretaceous sediments. The Tertiary sequence is complex, with facies relationships between a series of lithological units varying from neritic limestones (Duddo Limestone), shallow near-shore marine clays and marls (Netherby Marl, Geera Clay, Winnambool Formation, Bookpurnong Beds), paralic sediments (Knight Group), and non-marine fluviatile sands, silts, and clays (Wunghnu Group). The marine units are grouped as the Murray Group in contradistinction to the underlying paralic Knight Group and the non-marine Wunghnu Group on the landward side. The littoral marine Yanac Member at the base of the Netherby Marl represents the initial rapid transgression of the Murray Group; the regressive phase is expressed in part by the Diapur Sandstone, interpreted as a complex of stranded coastal features whose ridge topography represents successive stages of the regression. The Quaternary sequence is a complex of aeolian and fluvio-lacustrine sediments, divided in a sequence of thin units and members: Lowan Sand, Woorinen Formation (6 members), Blanchetown Clay and Bungunnia Limestone, Shepparton Formation (6 members), Coonambidgal Formation, and lunettes; the sequence being terminated by late Pleistocene to Recent evaporites (calcite, halite, and gypsum). The Shepparton and Coonambidgal Formations constitute the higher part of the Wunghnu Group. Many of these formation names are new; the members are adapted from previous informal usage by soil scientists.

Introduction

The area discussed in this paper covers the Mallee Region, an official resources district comprising 14,394 square miles of NW. Victoria and constituting just under 15%, by area, of the large sedimentary unit known as the Murray Basin (Fig. 1). The Tertiary sediments of the basin range in age from Lower?-Middle Eocene to Recent and include clay, silt, sand, gravel, marl, limestone, lignite, and glauconitic sediments. They are classified into rock units which generaly thicken and dip gently towards a point immediately W. of the NW. corner of Victoria. The main pre-Tertiary units consist of Lower Cretaceous marginal marine sands and shales, probable Lower Permian fluvioglacials, granites of unknown age, and Cambrian to early Ordovician metasediments.

Two distinct Tertiary depositional sequences are recognizable. These may correspond with the two youngest depositional cycles of the four-cycle system discriminated by Bock & Glenie (1965) for the Late Cretaceous to Tertiary sequence of the Otway Basin. For the youngest sequence in the Murray Basin there are some striking similarities with cycle 4 in the Otway Basin, but uncertainties exist with equating the earlier sequence—it has the broad time equivalence of cycle 3 but shows closer lithological affinities with cycle 2.

The main difference between the two sequences in the Mallee Region is that the older one consists essentially of carbonaceous clastics, whereas the younger sequence consists predominantly of calcareous rocks. Tertiary sedimentation in the Murray Basin was connected with gravity sag, which determined its geographical location, and perhaps with regular eustatic changes of sea-level.

Because the Tertiary sediments in the Mallee Region are almost completely buried by a veneer of Quaternary sediments, our knowledge of them is derived mostly from drilling. There are few publications on the subsurface geology of the Mallee Region; the main ones are: Chapman (1916), on the lithologic and palaeontologic description of samples from a line of 11 bores extending eastward from Panitya to Tutye; and Gloe (1947), who has given an exhaustive compendium of bore-hole data from private and official bores in the Mallee, Wimmera, and Glenelg Regions, and the hydrogeological interpretation of this data.

Since these publications, numerous deep bores have been sunk in the Mallee Region by the Victorian Mines Department as part of a groundwater survey of that Region. Because this drilling programme has been directed primarily for groundwater exploration and because the Murray Basin is relatively shallow, percussion plants have been used almost exclusively in preference to rotary drills; accordingly, sludge samples are virtually the only record of the strata passed through. The only rotary drilled holes in the Mallee Region from which cores of the strata have been taken are Olney No. 1, in the far NW. corner, and Mournpoull No. 1 at Hattah. These two bores are also the only ones in the Mallee Region to be electrically logged. Bore-hole data from the surrounding areas outside the Mallee has been studied to supplement this data.

The stratigraphy of the Cainozoic sediments in the Mallee Region is related to that in the neighbouring regions; where possible I have attempted to apply this work. For those portions of South Australia and New South Wales adjacent to the Mallee Region, the main published contributions are by Kenny (1934), Ludbrook (1961), Mulholland (1940), O'Driscoll (1960), and B.M.R. Publication 52, Petroleum Search Subsidy Acts (1964). The Tertiary stratigraphy of the Mallee Region has been correlated as closely as possible with the sequence established for the South Australian portion of the Murray Basin by Ludbrook (1957, 1958, 1961, 1963). Although Hills (1939) described the physiography of NW. Victoria and of the Mallee Region in particular, little detailed mapping of the Quaternary sediments of the Murray Basin as a whole had been done until recent years. The main contributor to this work, in so far as it is applicable to the Mallee Region, is Butler (1950, 1956, 1958, 1959) who, from reconnaissance mapping, provided a means of subdividing outcropping Quaternary sediments of the Murray Basin on the basis of lithology, genesis, and paleosols. This pioneer work has been followed by Churchward (1960, 1961b, 1963a, 1963b, 1963c) who has subdivided the material of the E.-W. dune chains in the Swan Hill district by applying Butler's criteria for recognition of buried soils, and by Pels (1964) who has discussed the distribution and evolution of the 'Coonambidgal' of Butler (here used as Coonambidgal Formation) associated with the Murray River.

In the following outline of the stratigraphy of the Cainozoic sediments of the Mallee Region the emphasis is on lithology.

For the gross stratigraphy of the Tertiary sequence, Ludbrook's rock units are adopted where possible, but it has been necessary to redefine some of these and also to introduce new ones.

The discussion under the heading 'Quaternary' is subdivided partly by rock units and partly by geomorphic forms, e.g. lunettes. The formations of Quaternary age are broadly subdivided into two types of deposition, namely aeolian units (dunes, sheets, lunettes, source-bordering dunes), and alluvial units (pediment, channel, flood-plain, and lacustrine), marked at the top by a soil and commonly at the base by a disconformity. Each formation is, in turn, subdivided into members which are used in a similar sense to formations except that they may be only locally

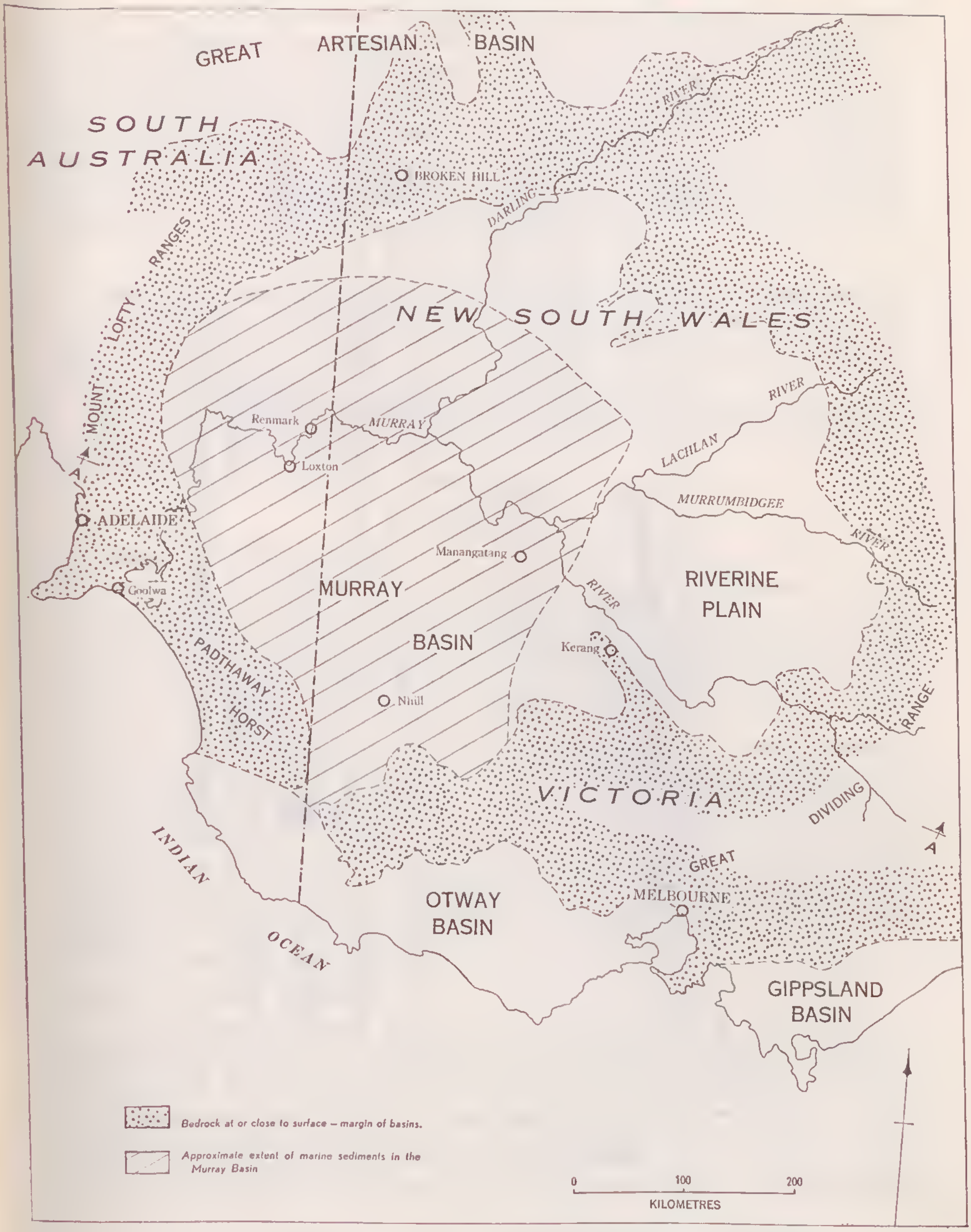

FIG. 1—Map of SE. Australia showing the location of the Murray Basin.

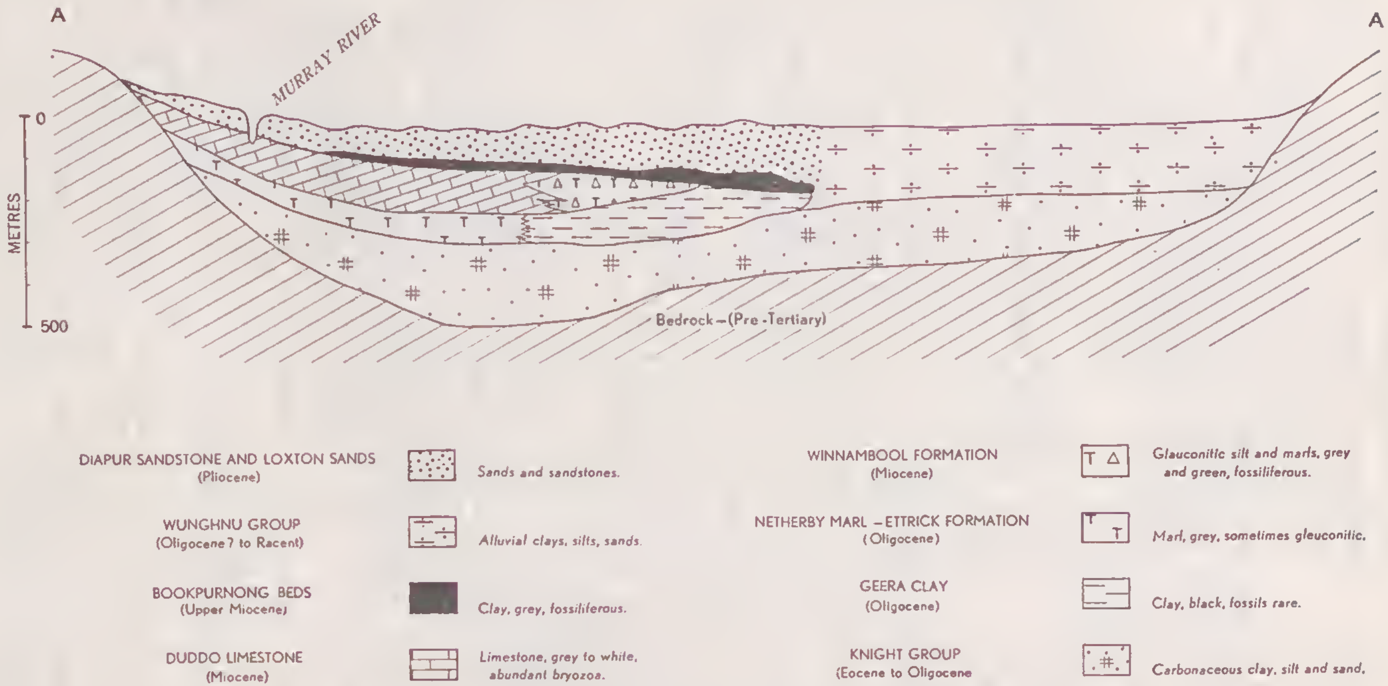

FIG. 2—Diagrammatic geologic section across the Murray Basin.

identifiable. Formal names used for members are adapted from the 'systems' and 'layers' of Butler and Churchward; these are regarded as more or less equivalent to members. The type locations and definitions by pedologists of these informal units are incorporated within the lithostratigraphic redefinition of members discussed in this paper. The soil designations K1s, K2s, K3s, K4s, and K5s, as defined by Butler (1959) are retained. The symbols of the K cycle are employed in this paper principally because they provide a means of communication between Quaternary geologists and stratigraphic pedologists working on the Murray Basin. In doing so, the author is aware of the undesirable connotations associated with the K cycle because of present widespread and indiscriminate use.

Acknowledgements

I gratefully acknowledge the guidance and interest of Dr D. E. Thomas, Director of Geological Survey. I am indebted to Dr J. A. Talent for his encouragement and constructive criticism of the manuscript. I have benefited from discussions with Messrs P. E. Bock, R. C. Glenie, M. W. Johns, and P. G. Macumber. Mr M. W. Johns also participated in the field work during the early stages.

Mr W. A. Esplan electrically logged the bores and advised on the interpretation of these logs; Mr D. J. Taylor identified Foraminifera and Mr J. G. Douglas identified fossil plant material.

Stratigraphy

Basement Rocks

Cambrian? Metasediments

Underlying the Mallee Region, and invariably buried with angular unconformity beneath the Knight Group are metamorphics of probable Cambrian to Lancefieldian age derived from fine to medium-grained clastic sediments. Rock types listed in Johns & Lawrence (1964) include shale, slate, phyllite, and sericite schist. Intruding these metasediments are granite bodies and quartz veins. Granite outcrops in the E. portion of the Mallee Region at Wycheproof, and near L. Boga where it shows copper and uranium mineralization.

When buried, the Cambrian? metasediments and granites are highly weathered to white, grey or buff clay; this material has been cored from only one bore in the Mallee Region—Mournpoull No. 1. The weathering process may be attributable to either the action of the acidic, bicarbonate-rich groundwater in the Knight Group acting on the basement rocks, or aerial and chemical weathering of the basement rocks prior to their burial. The composition of the weathered basement rock is generally kaolinite and quartz, but only in two cases has its composition been analysed by the X-ray diffraction method. The composition of weathered sericite schist from a depth of 1,370-1,380 ft in the Walpeup No. 2 bore was muscovite 40%, kaolinite 40%, and quartz 20%.

Lower Permian? Sediments

Lower Permian sediments have not been encountered so far in drilling in the Mallee Region; however, it is inferred from what is known from surrounding areas that they are present. Immediately S. of the Mallee Region at Netherby in Warraquil No. 1 bore, 1,385 ft of tillite and sandstone were encountered between the depths of 981 and 2,366 ft; in New South Wales, the Wentworth No. 1 bore encounted silty clay to siltstone of Permian age between 1,604 and 2,055 ft, and conglomerate of Permian? age between the depths of 2,055 and 2,081+ ft; in South Australia, the North Renmark bore encountered glacial marine sediments between the depths of 3,245 and 4,018 ft.

Lower Cretaceous Sediments

Lower Cretaceous sediments have been penetrated in the Mallee Region only in the Olney No. 1 bore where a fissile, grey sandy siltstone was struck beneath Eocene sands of the Knight Group between 1,992 and 2,015 ft, at which depth the bore bottomed. A core taken between 2,001 and 2,013 ft contained both plant remains and arenaceous Foraminifera indicating an Albian-Aptian age. J. G. Douglas (pers. comm.) reports: 'Microspores included *Cicatrecosisporites australiensis* (Cookson) Potonié, *Lycopodiumsporites austroclavatidites* (Cookson) Potonié, *Coptospora paradoxa* (Cookson & Dettmann), *Rouseisporites reticulatus* (Pocock), *Aequitriradites* sp., *Microcachyridites antarcticus* (Cookson), *Pyrobolospora reticulata* (Cookson & Dettmann). Cuticular remains derived principally from remnants of

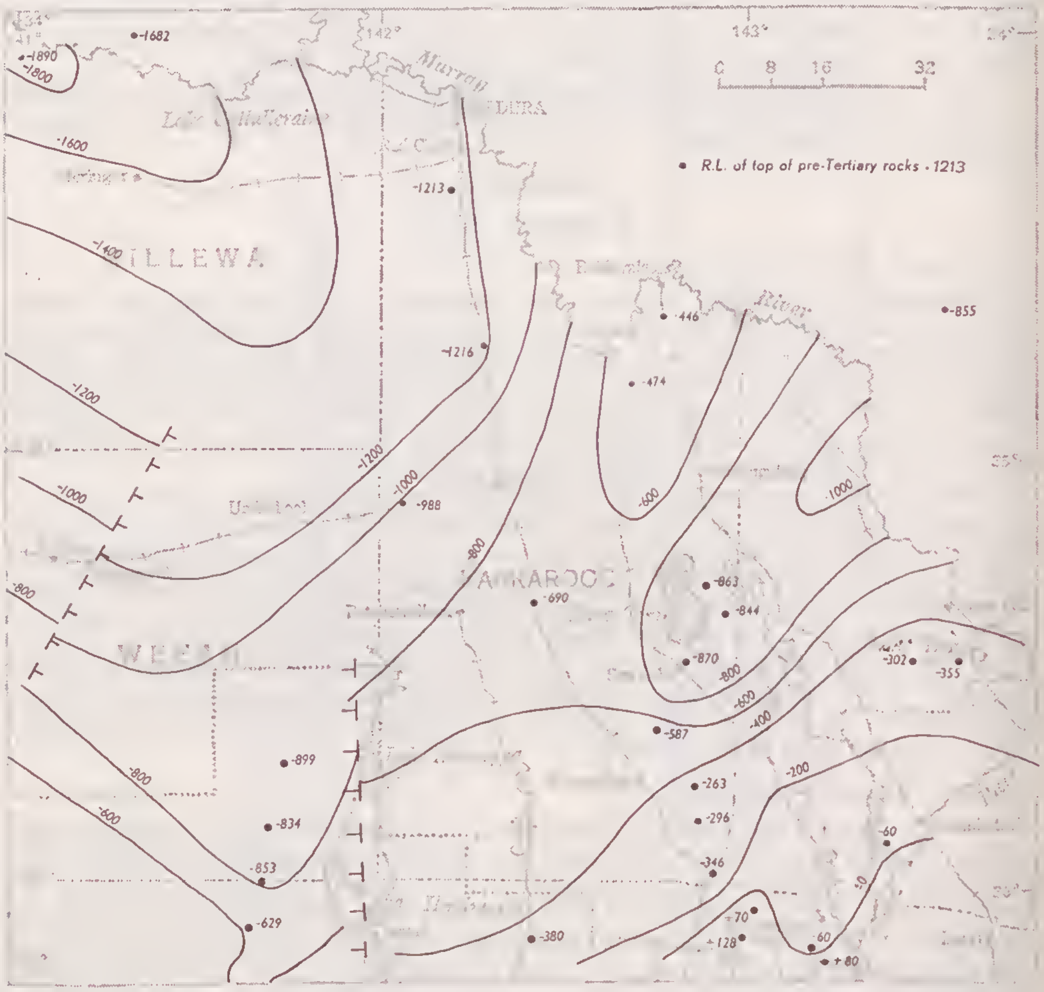

Fig. 3—Structure contours of the pre-Tertiary surface of the Mallee Region.

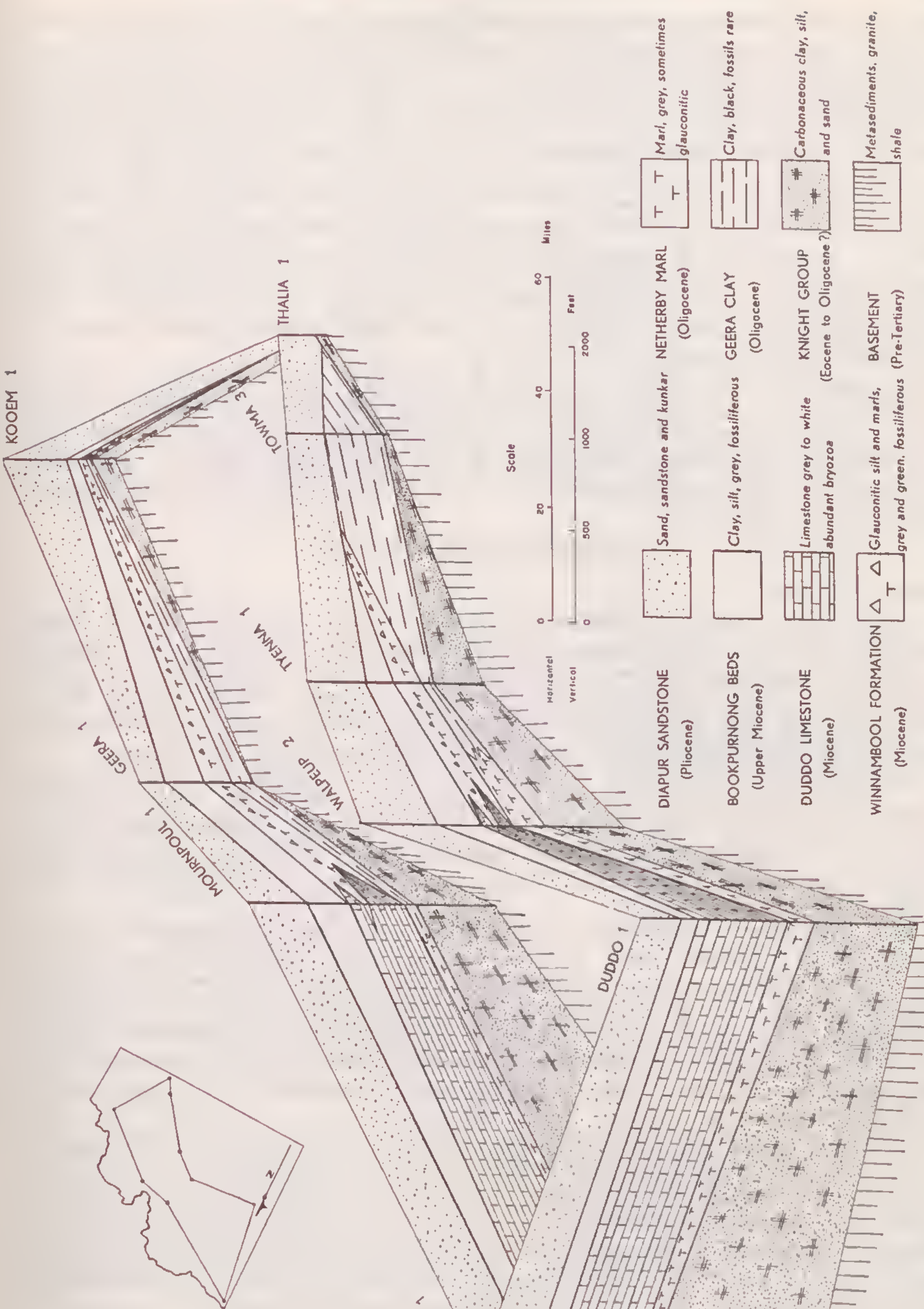

FIG. 4—Panel diagram of Tertiary rock-units in the Mallee Region.

large strap-like conifer leaves and a small-leaved *Brachyphyllum* type conifer were common. The microspore-megaspore remains indicate that the sample belongs to the *Paradoxa* Assemblage of Dettmann (1963) which she regards as belonging to the uppermost stages of the Lower Cretaceous. The cuticular remains (two types of conifer leaves) have been isolated from a number of localities in Western Victorian sediments also regarded as upper Lower Cretaceous in age (Douglas MS)'.

Although the Lower Cretaceous sediments were only partially penetrated in this bore, there are two bores adjacent to the Mallee Region in neighbouring States which have fully penetrated the Lower Cretaceous sediments. They are the North Renmark No. 1 (S.A.) and the Wentworth No. 1 (N.S.W.); in each case the Lower Cretaceous sediments, whose thicknesses were 840 ft and 331 ft respectively, rested unconformably on Lower Permian sediments (B.M.R. 1964). The Lower Cretaceous sediments in the far NW. corner of the Mallee Region probably occupy a similar stratigraphic position.

Ludbrook (1961) and the B.M.R. (1964) have implied correlation of the Lower Cretaceous sediments in the Murray Basin with those in the Great Artesian Basin. Indeed, it seems likely that the inundative phase of the depositional cycle responsible for the Rolling Downs Group also affected the Murray Basin area, depositing terrestrial and marginal marine time equivalents of the Roma Formation and the Tambo Formation.

Tertiary Sediments

Knight Group

The Knight Group, as defined by Sprigg (1952) and Boutakoff & Sprigg (1953), is a series of sands and carbonaceous sediments forming the lower part of the Tertiary sequence. Outcrops of the Knight Group are restricted to the raised belt of Tertiary rocks at the junction of the Otway Basin and the Murray Basin. It is in this belt, near Mt Gambier, but within the Otway Basin, that Boutakoff & Sprigg (1953) selected Knight's Quarry as the type locality of the Group.

The junction of the Knight Group in the Mallee Region with the underlying rocks may be either unconformable or disconformable. Where the underlying rocks are the tightly folded Cambrian? metasediments and their granite intrusives the junction is in angular unconformity. Elsewhere, for relatively small areas, the Knight Group rests disconformably on Lower Cretaceous sediments and probably on Lower Permian sediments.

The lithologies of the Knight Group include fine to medium-grained quartz sands; silts and siltstone which may be carbonaceous, dolomitic, or calcareous; clay, usually carbonaceous; and lignite. Pyrite and marcasite, both in authigenic and disseminated forms, are important accessories. The various rock types form an array of alternating and intertonguing strata for which there has been insufficient reliable information to establish stratigraphic subdivision. However, the calcareous and dolomitic siltstones appear to be almost exclusively restricted to the upper part of the Knight Group.

Preserved in the carbonaceous clays and lignite, but absent from the coarser clastics, is a rich assemblage of pollen derived from the temperate and tropical terrestrial plant genera *Casuarinidites, Myrtaceidites, Nothofagus, Proteacidites,* and *Triorites.* Marine fossils, almost exclusively the Foraminifera *Cyclammina* and *Cibicides,* are very rare. They are usually restricted to the upper part of the Knight Group in the W. part of the Mallee Region. Elsewhere, the lack of marine fossils, the variable lithologies and thicknesses, the poor sorting of many of the clastics,

TABLE 1

Cainozoic Stratigraphy of the Mallee Region

AGE		CLIMATIC EPISODES	← west	AEOLIAN			ALLUVIAL east →		
QUATERNARY	Recent	Man's influence		Lowan Sands	Woorinen Formation	Piangil Member	WUNGHNU GROUP		Coonambidgal Formation (several phases)
QUATERNARY	Recent	Arid		Lowan Sands	Woorinen Formation	Kyalite Member	WUNGHNU GROUP		Coonambidgal Formation (several phases)
QUATERNARY		Humid / Arid		Lowan Sands	Woorinen Formation	Speewa Member	WUNGHNU GROUP		Mayrung Member; Widgelli Member (aeolian); Quiamong Member
QUATERNARY		Humid / Arid	? ↑ / Bungunnia Limestone	Lowan Sands	Woorinen Formation	Bymue Member	WUNGHNU GROUP	Shepparton Formation	Katandra Member
QUATERNARY	Pleistocene	Humid / Arid	Blanchetown Clay	Lowan Sands	Woorinen Formation	Miralie Member	WUNGHNU GROUP	Shepparton Formation	Kialla Member
QUATERNARY	Pleistocene	Humid / Arid	Blanchetown Clay	Lowan Sands	Woorinen Formation	Unnamed Member	WUNGHNU GROUP	Shepparton Formation	Unnamed Member

AGE			LOCAL STAGES	MARINE INFLUENCE Western-part Mallee Region	MARINE INFLUENCE Eastern-part Mallee Region	NO MARINE INFLUENCE Northern Plains
TERTIARY	Pliocene	U		MURRAY GROUP: Diapur Sandstone	Diapur Sandstone	WUNGHNU GROUP: Wyuna Sandstone
TERTIARY	Pliocene	L	Kalimnan	Diapur Sandstone	Diapur Sandstone	WUNGHNU GROUP
TERTIARY	Miocene	U	Mitchellian and Cheltenhamian	Bookpurnong Beds	Bookpurnong Beds	WUNGHNU GROUP
TERTIARY	Miocene	M	Bairnsdalian; Balcombian	Duddo Limestone	↓ ? Winnambool Formation	WUNGHNU GROUP
TERTIARY	Miocene	L	Batesfordian; Longfordian	Duddo Limestone	Winnambool Formation	WUNGHNU GROUP
TERTIARY	Oligocene	U	Janjukian	Netherby Marl; Yanac Member	Geera Clay	? ↑ KNIGHT GROUP
TERTIARY	Oligocene	M-L		(hatched)	(hatched)	(hatched)
TERTIARY	Eocene			KNIGHT GROUP	KNIGHT GROUP	KNIGHT GROUP

Note:- Although boundaries of rock units in the table are represented as synchronous ones, some are known to be diachronous and the lack of continuity of strata indicate a non-marine environment of deposition —probably including fluviatile, lacustrine, and paludal types.

Only a broad Lower Tertiary age based on palynological evidence can be assigned to the Knight Group of the Victorian portion of the Murray Basin. Foraminifera present are *Cyclammina* and *Cibicides* which are long ranging species. However, it is considered, on micro-fossil evidence available, that deposition of the Knight Group in the Mallee Region began in the Lower Eocene and terminated in the W. portion of the Mallee Region in the Upper Eocene. The Knight Group in the Murray and Otway basins seems to be in part the landward equivalent of the marine-influenced Buccleuch Group (Ludbrook 1963) and the marine Nirranda Group (Bock & Glenie 1965). It is of similar facies to the Wangerrip Group but much of it appears to be younger than the latter in its typical development in the

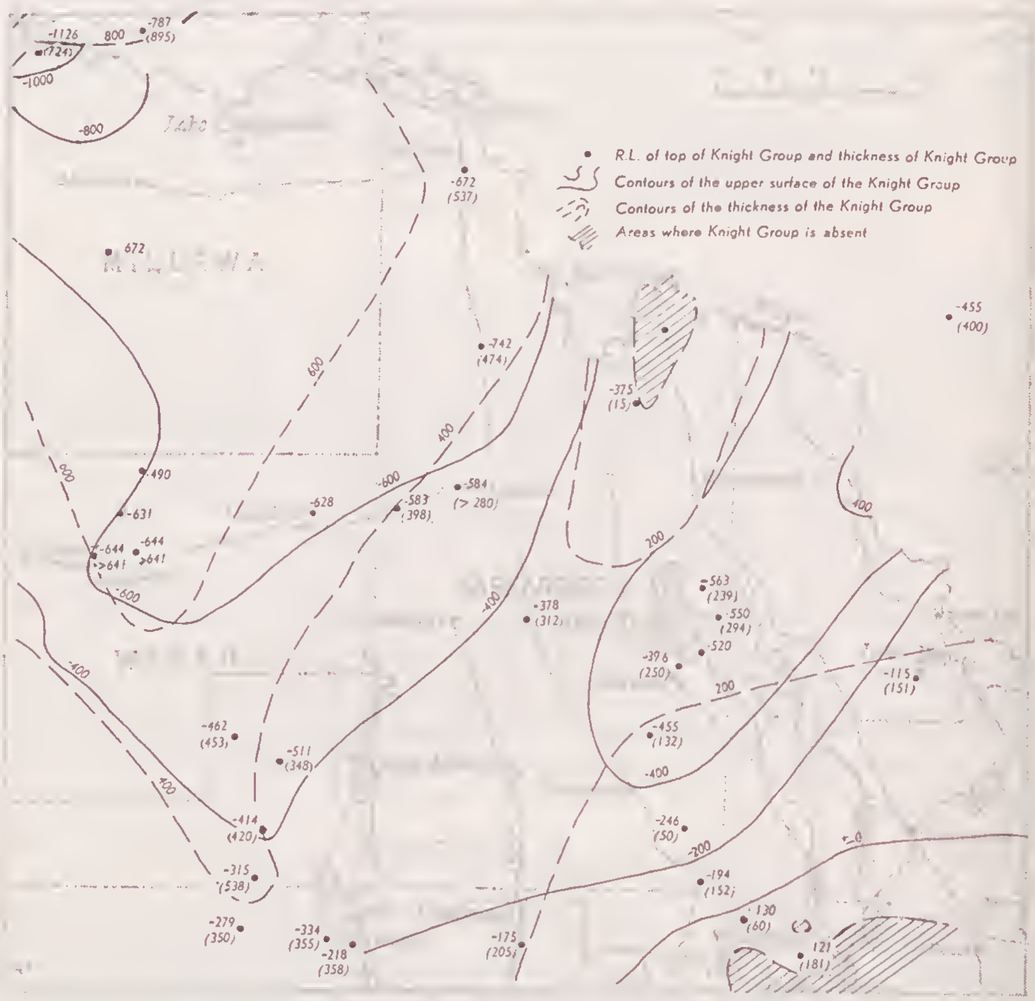

FIG. 5—Structure contours of the upper surface and isopach contours of the Knight Group in the Mallee Region.

W. Otway Basin and, unlike the latter, is not known to extend down to Paleocene and older horizons in the Murray Basin.

The Knight Group extends as an almost continuous unit throughout the entire Mallee Region, except where prominent bedrock 'highs' have precluded Knight Group sedimentation. Outcropping granite 'highs' at Wycheproof and L. Boga have prevented deposition of Knight Group sediments over small areas. In the Robinvale-Winnambool district, two bores—Bumbang No. 1 and Geera No. 1, the only bores to bedrock in that district—each traversed less than 10 ft of sands and gravel (Knight Group?) above bedrock. From geophysical and hydrogeological studies there is good evidence that this bedrock high, accompanied by the virtual exclusion of Knight Group deposition, extends northward from Winnambool into New South Wales.

From isopachs of the Knight Group in the Mallee Region (Fig. 5) it can be seen that it generally thickens towards the north-west. For example, it is 60 ft thick at Thalia in the far south-east and 724 ft thick in the far north-west in the Olney No. 1 bore. However, this trend is not constant. The main irregularity is the thickening of the Knight Group in the Piangil district to about 400 ft, a figure based partly on the author's stratigraphic interpretation of the logs of the Bundy No. 1 bore (N.S.W.) and the Balranald No. 1 bore (N.S.W.) published by the B.M.R. (1964).

Structure contours of the upper surface of the Knight Group have also been drawn (Fig. 5), but their value for interpretation of the history of the Mallee Region is dubious because the upper surface of the Knight Group, as presently defined, is diachronous. Nevertheless, some anomalies in the regional dip of the upper surface of the Knight Group are interpreted as being of tectonic rather than facies origin, e.g. the upper surface of the Knight Group is more than 150 ft lower on the E. and downthrown side of the Danyo Fault (Johns & Lawrence 1964) than the W. and upthrown side of this fault; also the upper surface of the Knight Group is lower (by more than 100 ft) on the W. side of the Hindmarsh Fault. Another irregularity in the general regional trend is a broad and low syncline trending SW.-NE. beneath L. Tyrrell and Piangil into New South Wales.

Being the most widespread of the rock units of the Tertiary sequence in the Mallee Region, the Knight Group is contiguous with several overlying younger units. Hence, the criteria employed to discern the upper boundary of the Knight Group, which represents a regional disconformity, depend on the lithology of the overlying rock-units. Where the Knight Group is buried beneath Oligocene marine sediments (Netherby Marl including the Yanac Member, and the Geera Clay), the upper boundary is easy to pick by the first appearance, as one drills down, of clastics or carbonaceous sediments devoid or almost devoid of marine fossils. East of a line linking Birchip and Swan Hill, fossiliferous marine sediments are absent and instead there are continental clays, silts, sands, and gravels, which together comprise the Wunghnu Group, resting on the Knight Group. The sole criterion used to select the upper boundary of the Knight Group in this case is the first sign in depth of persistently carbonaceous sediments, although some of the overlying non-carbonaceous sediments may be lateral equivalents of Knight Group sediments beneath the marine sediments to the west.

In the W. part of the Mallee Region, the Knight Group is disconformable beneath Janjukian strata belonging to the Yanac Member of the Netherby Marl, or, farther E., to the Geera Clay. Still farther E., continental sediments belonging to the Wunghnu Group, whose exact age is unknown, overlie the Knight Group. This means that, although there is a definite upper limit in age for the Knight

Group in the W. part of the Mallee Region where marine sediments are present, the upper limit is not precise in the east where there are palaeogeographical grounds for inferring that the upper limit of the Knight Group may extend higher. It is conceivable that the transgressing Oligocene-Miocene sea was fringed by marshes in which there could have been carbonaceous sedimentation.

Murray Group

Where marine influence is apparent in the Murray Basin, the depositional cycle has been used as the basis of classification at the group level; the older cycle is known as the Knight Group; the younger calcareous cycle is referred to as the Murray Group. The term 'Murray Group' was introduced by Ludbrook (1957) for the Miocene sediments lying between the Bookpurnong Beds and the Ettrick Marl. Its use in this paper has been broadened to include, besides the Duddo Limestone, all Tertiary marine sediments younger than the Knight Group.

The oldest unit of the Murray Group is the Yanac Member of the Netherby Marl; it consists of glauconitic micaceous clay and sand containing reworked Knight Group material. The Yanac Member represents a rapid marine transgressive deposit. It grades upward into grey marls of the Netherby Marl which thicken both southward and eastward away from the NW. corner of the Mallee Region where the sea is believed to have been deepest during Oligocene times. Farther eastward, the Netherby Marl grades into the dark grey to black, slightly calcareous Geera Clay. Clay-sized and silt-sized terrigenous material had an adverse effect on the benthic fauna which is limited to only a few species of Foraminifera and turrittelids. This is followed by a more extensive marine trangression during which the Duddo Limestone, containing a diversified fauna, was deposited. The limestone may be classified as a calcilutite or as a biosparite (Folk 1959), in which there is a small proportion, always less than 12%, of clay or sand-sized terrigenous material. The limestone because of its high proportion of sparry calcite particles (generally 10μ to $20\ \mu$ in diameter), suggests a moderately high energy environment.

Eastward and landward of the Duddo Limestone is the glauconitic silty or marly Winnambool Formation which grades in turn into the black almost unfossiliferous Geera Clay. By comparing these sedimentary zones with the model produced by Irwin (1965) for epeiric clear-water sedimentation it is evident that, for the Mallee Region, there was an abundance of fine grained material available from an eastern source. Both the Winnambool Formation and Geera Clay are considered to have been deposited in a low energy environment. The abundance of terrigenous sands carried by river water is regarded as the prime cause of the poor and unusual fauna present in the Geera Clay.

The regressive part of the cycle is prolonged, indicating a gradual withdrawal of the sea. A succession of sediment types is represented. The glauconitic, fossiliferous and clayey Bookpurnong Beds overlie the Duddo Limestone and Winnambool Formation. Overlying the Bookpurnong Beds is the unfossiliferous Diapur Sandstone, silty near the base but sandy through the rest of the profile.

Netherby Marl—

The Netherby Marl is named after the township of Netherby (in the Wimmera Region) where the bore, Warraquil No. 3, serves as the type section.

The Netherby Marl is found only in the W. part of the Mallee Region: the Hindmarsh Fault marks its easternmost extent in the south; to the north its easternmost boundary probably trends NNW. to cross the Murray R. near Wemen. The thickness of this formation varies between 150 ft and 70 ft, thinning towards the north; its regional dip is towards the NW. corner of Victoria. Eastward, as shown in the geological section (Fig. 4) the Netherby Marl grades into the slightly calcareous, glauconitic clay and silt of the Geera Clay.

The dominant lithologic type of the Netherby Marl is marl, but, scattered throughout, sometimes there are thin beds of marly limestones (which may contain shelly fossils) and calcareous clays. Regionally, the Netherby Marl becomes more limey towards the centre of the basin, i.e. towards the NW. corner of the Mallee Region.

The mineralogical constituents of the Netherby Marl are clay, quartz, calcite, aragonite, glauconite, and chert. Clay and quartz grains are allogenic components —probably derived from redistributed Knight Group sediments and possibly from the weathering products of a variety of Palaeozoic rocks in the Central Highlands. The calcium carbonate is present as calcite and aragonite, mainly as microcrystalline sparry material, but also as the tests of fossils. Foraminifera are the dominant group, with Bryozoa, Mollusca, Pelecypoda, and Echinodermata present in much smaller numbers. Unlike the Foraminifera which are dispersed throughout the formation, the fossils of these other groups are usually concentrated in thin bands.

The presence of aragonite in significant amounts instead of calcite alone is probably because highly saline connate water entrapped in the Netherby Marl has retarded the conversion of aragonite to calcite. Nodules of dark grey chert, sometimes with included fossils, occur rarely and spasmodically in the Netherby Marl. Because fossils are included in these nodules it is thought that the formation of chert has been a post-depositional and diagenetic process.

A continuous sheet of whitish bryozoan limestone—the Duddo Limestone—rests conformably on the Netherby Marl throughout the Marl's entire extent in the Mallee Region. Outside the Mallee Region near the S. margin of the basin, the Duddo Limestone is irregularly preserved in relatively small areas; where the Duddo Limestone is absent, the Diapur Sandstone rests directly on the Netherby Marl. The junction between the Duddo Limestone and the Netherby Marl is clearly discernible in most drilled sections by the abrupt change from white permeable bryozoan limestone to a grey, impermeable marl; but there are some districts, such as the S. part of the Big Desert, where the junction is obscure because of a transition zone of interfingering thin beds of marl and limestone. In such cases, the upper boundary has been arbitarily selected as the first appearance of marl in depth within this transition zone.

Electric logs are useful in discriminating the boundary between the Duddo Limestone and the Netherby Marl. Opposite the Netherby Marl, the self-potential curve is relatively positive and the normal resistivity curve is uniformly low. By contrast, the normal resistivity curve is markedly higher and the self-potential curve is relatively negative opposite the Duddo Limestone. The differences in electric logs opposite these lithologies are caused principally by the contrast between permeable limestone and relatively impermeable marl, and by the higher salinity of the groundwater in the marls.

The distribution of the Netherby Marl and its biostratigraphy as outlined above differs from the preliminary picture presented by Gloe (1947) who suggested that the marls girdling the Dundas Highlands graded basinwards into limestones, thereby reflecting distance from the source of the terrigenous material. Recent biostratigraphic studies suggest that this change from marl to limestone deposition in late Janjukian times was a regional one involving the entire Murravian Gulf, presumably associated with tectonic activity as with the other Tertiary basins of SE. Australia.

From foraminiferal evidence based mainly on the sections in the Olney No. 1 and Coynallan No. 1 bores (situated outside the Mallee Region approximately 15 miles S. of Nhill) the Netherby Marl is correlated with the Janjukian stage. The following diagnostic Foraminifera were identified by D. J. Taylor from between 340 and 570 ft in the Coynallan No. 1 bore: *Globigerina apertura, G. ciperoensis, G. ouachitaensis, G. bispherica, G. rubra, G. triloba* (large aperture form), and *Globoquadrina dehiscens.* Palaeontologic and other evidence is pointing to the correlation of the Netherby Marl with the Ettrick Formation (Ludbrook 1957) found in the W. part of the South Australian portion of the Murray Basin. If, in the future, further evidence confirms this correlation then the senior synonym, Ettrick Formation, would be retained and the term Netherby Marl discarded.

Yanac Member—

The Yanac Member, named after the township of Yanac, S. of the Mallee Region, refers to very glauconitic clayey or sandy units at the base of the Netherby Marl.

The presence of glauconite (or oxidized pseudomorphs after it) throughout the Yanac Member is diagnostic and is indicative of the depositional conditions, i.e. marine environment in a temperate to warm temperate climate, accompanied by slow sedimentation under moderately reducing conditions. It is inferred that these conditions existed during deposition of the Yanac Member and were aided by the micaceous and carbonaceous fractions of the Knight Group which constituted the floor of the sea over which the Yanac Member was deposited, since biotite is one of the basic ingredients for glauconite formation and carbonaceous material would help create reducing conditions. The Yanac Member represents the earliest part of the rapid Janjukian trangressive phase, and its lower boundary, on micropalaeontological evidence, appears to be synchronous.

The Yanac Member rests disconformably on the Knight Group. The junction of the Yanac Member and Knight Group is sharp and easily discriminated. The Yanac Member is a green or orange coloured, fossiliferous, calcareous, fine-grained sediment and thus contrasts with the grey sand or brown carbonaceous sediments of the Knight Gorup.

An oxidized rock unit at a similar stratigraphic position to the Yanac Member persists throughout much of the Otway Basin; in South Australia it is referred to as the Compton Conglomerate, and in Victoria as the Clifton Formation.

Geera Clay—

The Geera Clay receives its name from the parish of Geera in the E. part of the Mallee Region, where the bore Geera No. 1 provides the type subsurface section. This bore, drilled by the Mines Department during 1961, cut the proposed formation between 490 and 590 ft; therefore, it has a thickness there of 100 ft. The surface level at the bore site is approximately 215 ft. Lithologically, the Geera Clay throughout its type section is a light olive grey to dark grey, fossiliferous clay in which glauconite grains are common.

Regionally, the Geera Clay is an olive grey to dark grey clay or silt which generally contains a poor fauna. The darker clay resembles the richly carbonaceous clays of the Knight Group in appearance, but in the Geera Clay the dark colour is due to iron minerals, particularly disseminated FeS_2; very little carbon is present.

Glauconite and pyrite are the dominant iron minerals, with melnikovite, siderite, and possibly some organic-iron complex making up the remainder; gypsum is sometimes present. Carbonate is present as the tests of what is usually a sparse, depauperate fauna of Foraminifera and Ostracoda; lacking is the Bryozoa so common in most other Tertiary marine units of the Murray Basin.

It is concluded that the Geera Clay was deposited in a shallow marine and lagoonal situation to which terrigenous muds were added; this would account for the poor fauna and the lithology. The fact that the iron is almost exclusively present as the ferrous form implies that the Geera Clay was deposited under reducing conditions. In the shallow seas which prevailed at that time, there must have been sufficient organic matter, probably derived from sub-aerial Knight Group outcrops, to deplete the oxygen dissolved in the sea water and reduce any ferric compounds to ferrous ones.

Although relatively few bores have penetrated the Geera Clay—a situation arising from the depth at which it occurs, and the presence of saline groundwater in the overlying Winnambool Formation—it appears to be distributed over a broad arc, landward from the Duddo Limestone, from Nurrabiel (in the Wimmera Region) through Birchip and Nyah into New South Wales.

Both the Netherby Marl and the Geera Clay correlate, on micropalaeontological evidence, with the Janjukian stage. From this and other stratigraphic evidence it appears that, to the east and to the north, the Netherby Marl grades laterally into the Geera Clay. This facies variation is sharpest where influenced by the tectonic control of the Hindmarsh Fault.

Briefly, the Geera Clay is a Janjukian transgressive deposit onlapping and disconformably overlying the Knight Group. The boundary between it and the Knight Group is identified in the same way as that between the Netherby Marl and the Knight Group discussed above.

DUDDO LIMESTONE—

For the South Australian portion of the Murray Basin 'proper', Ludbrook (1957) introduced three limestone formations, the Pata Limestone, Morgan Limestone, and Mannum Formation, all included in the Murray Group. The type localities for all these formations are near the W. margin of the Murray Basin; the type sections of the Morgan Limestone and the Mannum Formation are exposed in cliffs of the Murray River, whereas the type section of the Pata Limestone is in a shaft near Loxton. These outcrops of limestone are interpreted as inner neritic and littoral facies, an opinion supported by their position in the basin and their fossil assemblage. In this part of the basin there have been interruptions to carbonate deposition expressed as localized disconformities or changes of lithology, e.g. the Finniss Clay, the Cadell Marl Lens, and the transition bed of glauconitic sandy marl between the Pata Limestone and the underlying Morgan Limestone at the type locality of the former.

Interruptions to the calcareous suite of sedimentation typical of the W. margin of the Murray Basin become less frequent, and eventually disappear deeper in the basin in Victoria. The exception is a thin and discontinuous marly and glauconitic bed, possibly equivalent to the Cadell Marl Lens, lying 30 to 70 ft below the upper surface of the Duddo Limestone. E.g., in the Olney No. 1 bore a marly limestone bed 27 ft thick occurs 67 ft below the top of the limestone. The limestone above this marl bed is usually characterized by large numbers of *Ditrupa* sp.

The rarity of changes in the limestone sedimentation in the Victorian part of the Murray Basin means that the limestone formations of Ludbrook (1957) cannot be lithologically discriminated there; recognition of their equivalents must await detailed palaeontological work. These limestone formations are accordingly regarded as members of a new all-embracing formation—the Duddo Limestone. It is named after the parish of Duddo immediately N. of Murrayville; the Duddo No. 8 bore is selected as the type section. The Duddo Limestone encountered in this bore between 252 and 609 ft consists of greyish-white limestone, varying in texture from fine to medium-grained and containing some sand-sized quartz grains; the dominant fossils are Bryozoa and Foraminifera.

The nature of the E. boundary of the limestone varies. North of about the latitude of Patchewollock the limestone grades eastward, with some intertonguing, into the marly and silty fossiliferous Winnambool Formation, but farther south the limestone pinches out rapidly to the east along a N.-S. line, and is replaced by the Winnambool Formation. This sharp facies change is accounted for by Cainozoic movement on a bedrock fault—the Hindmarsh Fault. Northward, towards the New South Wales-Victorian border, the Duddo Limestone becomes noticeably thinner, suggesting that it does not persist far into New South Wales. The E. boundary of the limestone is thought to cross the Murray R. near Carwarp. The Duddo Limestone may well be continuous with the Gambier Limestone in the south near the junction of the Murray and Otway basins; the time ranges of these two limestone formations overlap (Ludbrook 1964, Fig. 1).

The Duddo Limestone is thickest in the far W. part of the Mallee Region, thickening from about 300 ft in the far south to 600 ft in the Olney No. 1 bore. Throughout most of its extent it displays a regional dip towards the NW. corner of Victoria, but this regional dip is reversed in the Murrayville district where movement on the Danyo Fault has resulted in a monoclinal flexure, the Duddo Limestone there dipping to the south-east.

The stratigraphic relationship of the Duddo Limestone to the confining strata, although known to vary from one locality to another within the Murray Basin, is consistent within the Mallee Region, where it rests conformably on the Netherby Marl and is in turn overlain conformably or with possible disconformity in places by the Bookpurnong Beds. The upper boundary of the Duddo Limestone is always a sharp and easily discernible change downwards from greenish to grey clays and silts of the Bookpurnong Beds to the pale greyish-white Duddo Limestone. The lower boundary of the Duddo Limestone is not always easily discernible because the change from limestone to marl is often gradational. Electric logs have proved to be of value in selecting the upper and lower boundaries of the Duddo Limestone, which has a more negative spontaneous potential and higher normal resistivity than for the confining strata.

The range of lithologies shown by the Duddo Limestone includes pure limestone to marly limestone and thin beds of marl, the limestone being fine-grained and varying from calciludite to calcarenite. Using the classification for limestones proposed by Folk (1959), the Duddo Limestone in the Mallee Region is generally a sparry biogenic calcirudite (biostparrudite) or a sparry biogenic calcarenite; sparry calcite cement composed of grains or crystals 10-60 μ in diameter is common in the limestone. The biogenic constituents consist of the calcareous remains of bryozoans, foraminifers, echinoids, ostracodes, pelecypods, brachiopods, and scaphopods. The rock is highly permeable and porous and is a high yielding aquifer. In each vertical section there are always several thin and hard, but apparently uncorrelatable, bands in which the calcareous fossil remains are bonded together with calcareous cement. In places thin beds of chert nodules are found; in others there are non-calcareous sands, silts, and clays, but, except for the clays, these are usually insignificant.

From the fossil assemblage of the Duddo Limestone it is possible to determine the conditions of the marine environment in which this formation was deposited.

Bryozoa, the dominant fossil group present, are mainly cellariiform, indicative of offshore conditions; associated eschariform Bryozoa indicate depths greater than 60 ft (Stach 1936, Cheetham 1963). Still-living bryozoan species found fossil in the Duddo Limestone indicate that the water of the Murravian Gulf at the time of limestone deposition was of normal salinity, and that the climate was probably temperate. Benthonic Foraminifera outnumber planktonic ones; this and the large number of echinoid spines are further evidence for neritic conditions.

Micropalaeontological examination of drilled sections of the Duddo Limestone in Victoria (Chapman 1916, Crespin 1946) has demonstrated the time equivalence of the Duddo Limestone to the combined time range of the three units (? members) discriminated in South Australia: Pata Limestone, Morgan Limestone, and Mannum Formation.

WINNAMBOOL FORMATION—

East from the Duddo Limestone are contemporaneous marine calcareous sediments of variable lithology, here referred to as the Winnambool Formation. This rock unit is named after the gazetted township of Winnambool, 31 miles S. of Robinvale; it is near here that the type bore section, Geera No. 1, is located.

In this bore the Winnambool Formation was encountered between 340 and 490 ft, a thickness of 150 ft. The lithology ranges from a medium to light grey, marly clay to marl, in which gastropods and pelecypods are common, bryozoan skeletons rare, and glauconite grains common. The lithology at the type section is more uniform than in most other bore sections; elsewhere it includes clays, silts, marls, and some thin beds of limestone; there is often sufficient glauconite present to impart an olive grey shade to the sediment.

Our knowledge of the Winnambool Formation is sparse; private bores sunk for groundwater have only partially penetrated it because of the highly saline groundwater it contains; relatively few official bores have been sunk through it to bedrock. At each of these latter sites the Winnambool Formation rests conformably on the darker, and far less calcareous Geera Clay. This boundary is arbitarily selected at the change in depth from fossiliferous calcareous sediments to persistent relatively fossiliferous non-calcareous sediments. The fossiliferous dark grey to dark green and usually silty clays of the Bookpurnong Beds rests, probably conformably, on the Winnambool Formation throughout much of its distribution.

Despite meagre knowledge, the Winnambool Formation is thought to cover a broad arc, extending from S. of Hopetoun through Tempy and Piangil into New South Wales. Towards the east it lenses out, thus grading into the Geera Clay both laterally and vertically.

Micropalaeontological evidence shows that the Winnambool Formation ranges from the Longfordian Stage probably up to and including the Balcombian Stage. From its regional relationships, its significant proportion of terrigenous material, and its shallow water fauna of pelecypods, gastropods, and echinoids, the environment of deposition of the Winnambool Formation is regarded as inner neritic.

BOOKPURNONG BEDS—

The Bookpurnong Beds were defined by Ludbrook (1957) as red and green micaceous and glauconitic marls. They are typically exposed in the bank of the Murray R., 2½ miles downstream from Loxton, adjacent to section 11, 100 of Pyap (S.A.). A drainage bore near Loxton, on section 377, 100 of Gordon, provides the standard subsurface section. In the South Australian portion of the Murray Basin the Bookpurnong Beds disconformably overlie the 'Pata Limestone

Member' of the Duddo Limestone and, in turn, are disconformably overlain by the Loxton Sands. The Bookpurnong Beds were assigned by Ludbrook (1964), on the evidence of Mollusca and Foraminifera, to the Kalimnan and Cheltehamian Stages, i.e. Upper Miocene to Lower Pliocene.

Sediments similar to the Bookpurnong Beds as defined by Ludbrook (1957), yet showing certain deviations in lithology and age from that of the original definition, occur in the Mallee Region. The sense in which the term Bookpurnong Beds is used here is broadened to accommodate the Victorian variations of this unit. Throughout the Mallee Region they consist of a dark glauconitic and calcareous or clayey silt containing carbonate—usually as tests of Mollusca, Foraminifera, and Ostracoda. Biotite is often present, and in places there are stages of its alteration to glauconite which, in turn, may be oxidized to limonite or ferruginous clay; pyrite is rarely present. The Bookpurnong Beds form an almost continuous unit throughout most of the Mallee Region, but they are absent from the most E. part. The formation is thinnest to the south, in the S. half of the county of Weeah, where it probably persists over several thousand square miles as a 5 to 10 ft thick clayey unit. Northward there is a marked increase in the thickness, e.g. in the Yatpool No. 1 bore it is 235 ft thick and in the Olney No. 1 bore it is 212 ft thick.

The Bookpurnong Beds conformably overlie the Duddo Limestone and the Winnambool Formation except for possible disconformities towards the S. margin of the Murray Basin. This contact is generally distinct, although towards the east the underlying Winnambool Formation becomes more clayey and glauconitic, approaching the Bookpurnong Beds in character.

The time-range of the Bookpurnong Beds is related to some extent to its thickness. Where the Bookpurnong Beds are thin (as in the Warraquil No. 1 bore, situated at Netherby S. of the Mallee Region), the microfauna suggests correlation with the Cheltenhamian stage alone, but where the Bookpurnong Beds are thicker the microfaunal evidence suggests correlation with the Kalimnan, Mitchellian, Cheltenhamian stages and sometimes with the Bairnsdalian stage as well. In South Australia, Ludbrook (1957) correlated the Bookpurnong Beds on foraminiferal and molluscan evidence with the Kalimnan and Cheltenhamian stages. Accordingly, if the Bookpurnong Beds are considered on a regional scale, both its upper and lower boundaries are diachronous, with the formation as a whole being progressively older eastward.

The presence of *Elphidium* sp. and Miliolidae, the fact that it is the last regionally persistent fossiliferous marine formation in the Victorian portion of the Murray Basin, its high proportion of terrigenous material, and its diacroneity all suggest that the Bookpurnong Beds are offlap deposits from the upper neritic to littoral zones of the slowly retreating seas of the Murravian Gulf.

DIAPUR SANDSTONE—

The Diapur Sandstone, named after the township of Diapur in the Wimmera Region, is typically exposed in a railway cutting 2 miles W. of that township. It refers to the clastic regressive part of the Tertiary sequence of the Murray Basin in Victoria. This formation is similar to the Loxton Sands which were defined as 'cross-bedded, coarse, gritty, micaceous sands with shelly bands' (Ludbrook 1957), but differences of lithology and fossil content warrant their separation. The Diapur Sandstone is almost entirely fine to medium-grained sand, slightly micaceous, and unfossiliferous; strong cross-bedding is unknown. The Diapur Sandstone forms long, prominent topographic ridges, which are not apparent in the Loxton Sands. The junction of the Diapur Sandstone and the Loxton Sands, both considered to be facies variants of the one continuous regressive sequence, is thought to lie somewhere in the South Australian portion of the Murray Basin.

The foregoing discussion of the Diapur Sandstone has been largely based on bore-hole data for it is exposed in only a few isolated localities either at blowouts or as cliffs (up to 30 ft high at Red Bluff and Concertina Rocks in the Big Desert), in quarries, as at Nyah.

The lithology of the Diapur Sandstone is remarkably uniform. Mechanical analyses of outcrops show it to be fairly well-sorted, fine to medium-grained, and the proportion of clay usually less than 15% except towards the base where this proportion is usually higher. Quartz predominates, though there is some felspar and generally about 2% by weight of heavy minerals including limonite-coated quartz grains, zircon, and tourmaline. The uppermost 10 to 50 ft of the Diapur Sandstone

Fig. 6—Structure contours of the base and the position of the main ridges of the Diapur Sandstone in the Mallee Region. Note, this formation is absent in the SE. corner.

is cemented with limonite imparting a light brown to moderate reddish brown colour; cementation by silica is rare. Generally there is a zone at the top where the limonite has a pisolitic form, but the formation becomes mottled beneath this, the proportion of reddish-brown mottles decreasing with depth; the intergranular interstices are rarely completely filled.

The mobilization of iron and its concentration in the upper part of the Diapur Sandstone is attributed to post-depositional weathering processes. In fact, the profile is at times similar to a lateritic profile (*sensu lato*). The silicified sandstone, known variously as duricrust (Woolnough 1928), silerete and 'grey billy', found at Rock Holes in the Sunset Desert and common in the SW. part of the New South Wales portion of the Murray Basin, has already been attributed a similar origin to that of laterites (Northcote 1951).

Near the S. margin of the basin the lateritized horizon developed on the Diapur Sandstone rises up into the Dundas Highlands where it is developed on the 'tableland' deposits. It is generally held that the time of laterization was Pliocene, but there is evidence of its partial development on Quaternary alluvial members in the Northern Plains. This suggests that 'laterization' in Victoria, although apparently active in Upper Pliocene times, continued intermittently into the Quaternary.

Beneath the limonite cemented surface of the Diapur Sandstone, there is very little to no limonitic cement to bind the quartz grains together; the formation is then represented by loose sand. This sand is yellow to reddish-brown in colour for depths ranging from 50 to 250 ft, below which depth the colour changes to greyish shades. This colour change corresponds to the level of the main water-table, and is due to the change from reduced iron compounds in the saturated zone below the water-table to oxidized iron above. Another contributing factor to the colour change may be the increasing proportion with depth of the clay-silt fraction in the Diapur Sandstone.

The depth to the water-tables shows up clearly on electric logs by a marked decrease from the very high normal resistivity opposite the oxidized and unsaturated zone of the Diapur Sandstone to much lower normal resistivity opposite the water-table and its associated capillary zone.

The configuration of the Diapur Sandstone differs from the other Tertiary units of the Murray Basin sequence in that although it generally thickens from the S. margin of the basin towards the NW. corner of Victoria, its upper surface is moulded into a series of ridges. These ridges are up to several miles wide and up to 200 ft high, with these two dimensions directly proportional to one another; their profile may be either simple and approximately symmetrical, or complex. For the Victorian portion of the Murray Basin, the ridges of Diapur Sandstone are sub-parallel and generally trend in a NNW.-SSE. direction (Hills 1939). The main ridges forming prominent features on the surface are: one ridge consisting of three aligned segments trending NW. from Galaquil in the south, through Patchewollock to Meringur in the north; the Tyrrell Ridge extending from Watchupga in the south to Robinvale in the north (the easternmost of these ridges in the Mallee Region); and the Cannie Ridge which extends northward from Cannie into the Woorinen district (Fig. 6 and 7).

Data from bores sited on and beside the ridges of Diapur Sandstone at Walpeup (Mallee Region), Kaniva, Nhill (Wimmera Region) and Goroke (Glenelg Region) demonstrate that the configuration of the lower surface is independent of that of the upper surface. Structure contours drawn for the lower surface of the Diapur Sandstone in Fig. 6 show that this surface generally slopes towards the Hattah district, where in the Mournpoull No. 1 bore it was encountered at 214 ft below sea level. As suggested by Hills (1939) tectonism has had some effect on this surface. Uplift in the counties of Albert and Alfred in South Australia (Howchin 1929), and uplift in association with the Danyo Fault has resulted in an easterly-directed dip for the lower surface of the Diapur Sandstone in the W. portion of the Mallee Region. Moreover, there appears to be a N.-S. anticlinal structure within the Diapur Sandstone S. of Robinvale, where the lower surface of the sandstone dips to the west and to the east away from this line.

The Diapur Sandstone rests apparently conformably on the Bookpurnong Beds. The boundary is taken at the change from grey, unfossiliferous sands and silts of the Diapur Sandstone downwards to grey to olive grey, fossiliferous glauconitic clays and silty clays of the Bookpurnong Beds. The one known exception is in the Murraville-Pinnaroo district where the sands immediately above the Bookpurnong Beds contain marine calcareous fossils; these sands are tentatively correlated with the Loxton Sands.

Blackburn (1962a) suggested that 'the ridges represent dunes established at successive coastlines of the former Murravian Gulf'; he substantiated this claim with evidence that size-grading of the sandstone from the ridges is suggestive of an aeolian origin, and that all the ridges have sub-parallel alignment yet show terminal curvature near the Central Highlands and the several monadnocks of Palaeozoic rocks. The 'stranded coastal dune' hypothesis is supported, in my opinion, by bore-hole data revealing that the Diapur Sandstone immediately overlies Tertiary fossiliferous marine sediments. The Northern Plains lack both the Diapur Sandstone and Tertiary marine fossiliferous sediments. Their close association elsewhere is taken to indicate some sort of genetic relationship. Nevertheless, there are difficulties with this theory. There are no fossils known in the Diapur Sandstone, yet such material would be expected. The stranded Pleistocene coastal dunes in the Otway Basin are composed of calcareous aeolianite, the comminuted calcareous material having been derived from the remains of marine animals. But the lack of fossils, lime, or primary aeolian structures in the Diapur Sandstone may not preclude a dune origin because:

(a) Fossils would be expected to be scarce under conditions of rapid deposition and varying salinity
(b) Calcareous material deposited would be comminuted owing to deposition in such an environment; therefore, it would be more readily leached out by groundwater.
(c) Most important, the subsequent lateritization or deep weathering would have leached out all carbonates and obliterated all structures initially based on carbonate material.

Blackburn's (1962a) explanation of the Diapur Sandstone ridges is not applicable to the origin of the entire vertical section of this formation, for though the lithology is uniform laterally, the grain size generally decreases in depth. This could be explained by the lower part of the Diapur Sandstone being deposited under offshore to littoral conditions, and the upper material, forming the ridges, being shoreline deposits. The Diapur Sandstone and the Bookpurnong Beds, accordingly, would represent a well-developed regressive phase.

Because of lack of fossils, the Diapur Sandstone can be dated only by considering its stratigraphic relationship with dated rock units, confining it laterally and vertically. It is regarded as being in diachronous relationship with the underlying Bookpurnong Beds; at their easternmost extent these beds appear to have been deposited in the late Miocene times, but with the retreat of the seas there was the cessation of marine deposition in Lower Pliocene times in the far NW. part of the

FIG. 7—Surface contours of the Mallee Region.

Mallee Region and in adjacent South Australia. Disconformably overlying the Diapur Sandstone is the fluvio-lacustrine Blanchetown Clay and Bungunnia Limestone succeeded by the aeolian Woorinen Formation divided into a sequence of aeolian increments which are considered to have been deposited during dry and windy phases of the Quaternary climatic cycles. If this is correct, and due allowance is made for development of the lateritic profile, then the Diapur Sandstone is entirely pre-Quaternary, with deposition ceasing an appreciable time before the Pleistocene.

WUNGHNU GROUP

The Wunghnu Group refers to the post-Knight Group fluviatile and lacustrine sediments of the Northern Plains and to similar sediments in the Murray Basin W. of the Northern Plains. It is named after the township of Wunghnu, where

Mundoona No. 1 bore, selected as the type sub-surface section, was drilled by the Mines Department in 1960 and was continued and completed in 1962.

The Wunghnu Group is a continuous unit throughout the Northern Plains except where broken by monadnocks of Palaeozoic rocks. West of the Northern Plains it occurs around the N. margin of the Central Highlands and as sediments filling stream valleys. It occurs along existing streams as the Coonambidgal Formation in the Mallee Region; it is widespread in the Towaninny-Wycheproof district, parts of the Swan Hill district, and as a broad belt trending SSE. from Birchip. The following driller's log of a private bore 4 miles S. of Wycheproof shows the diverse types of lithologies of the Wunghnu Group and gives an impression of its thickness:

	Lithologic Description	Depth (ft) from	to
Wunghnu Group	Clay	0	159
	Sandstone	159	171
	Clay	171	200
	Sand	200	240
Knight Group	Brown coal	240	330
	Sand	330	331
	Ligneous clay	331	340
	Sand, fine-grained	340	354
	Ligneous clay	354	388
	Sand, coarse-grained	388	413
	Silty clay	413	419
	Sand, coarse-grained	419	421
Bedrock	Decomposed granite	421	492
	Granite	492	512

The upper surface of the Wunghnu Group is generally flat except for minor rises and sinuous shallow depressions. The lower surface of the Wunghnu Group rests with apparent disconformity on the Knight Group over most of its extent, but close to the outcrop of Palaeozoic rocks at Wycheproof and Charlton the Knight Group is absent and the Wunghnu Group rests with angular unconformity on the Lower Palaeozoic rocks. The criterion used to discern the boundary between the Wunghnu Group and the Knight Group is the first sign in depth of persistent carbonaceous beds (see driller's log above).

The nature of the junction of the Wunghnu Group with the Diapur Sandstone is not clear because of lack of exposures. It is assumed that those units of the Wunghnu Group which are contemporary with the easternmost Diapur Sandstone intertongue with it. The main differences between these two units are that the Wunghnu Group is highly variable in lithology, is mottled throughout its entire section and has a flat upper surface, whereas the Diapur Sandstone has a relatively uniform lithology, lacks mottling below a depth of about 50 ft and forms topographic ridges.

It is difficult to surmise the time at which deposition of the Wunghnu Group began, for the few fossils found so far are not diagnostic of age. All that is known is that there is continuous facies relationship across the Northern Plains and the Mallee Region, and that the Wunghnu Group, therefore, probably includes fluviatile and lacustrine sediments of the same age as the Diapur Sandstone, Bookpurnong Beds, Winnambool Formation, and Geera Clay to the west. But to what extent time equivalents of these latter are represented cannot be ascertained.

Numerous paleosols within the Wunghnu Group itself indicate diastems apparently caused by a combination of shifting stream patterns, climatic changes, and tectonic movement.

Quaternary Aeolian Deposits

Lowan Sand—

The Lowan Sand is named after the county of Lowan where it is exposed over large areas. Widely spaced traverses show it to be a greyish-yellow, fine to medium-grained, siliceous sand with a high degree of sorting (most pronounced near the crest of the dunes), low kurtosis, and positive skewness. Quartz is the predominant mineral, usually more than 98% by weight; the quartz grains are characteristically frosted and of high sphericity; the most common accessory minerals are muscovite, zircon, and tourmaline.

In Victoria, the Lowan Sand is mainly localized as huge 'tongues' extending eastward from South Australia. Of these tongues, the N. two lie within the Mallee Region forming the Big Desert and the Sunset Desert (Fig. 8).

The Lowan Sand is blown into dunes, generally 15 to 30 ft high, displaying an irregular pattern; vegetation is scant, the sand continuing to move eastward under the influence of strong westerly winds. The instability of these dunes has prevented pronounced soil development, although in the swales there are signs of slight clay illuviation. Separating the dunes are swales and a few extensive sand plains. Because of the irregular topography of the Lowan Sand, its thickness varies considerably from a few feet, to probably about 100 ft for some of the largest dunes. The upper surface of the Diapur Sandstone, where the Lowan Sand rests disconformably, has much more subdued topography than where buried by the Woorinen Formation. This is considered to be due to the more extensive deflation within the 'Deserts', where the Lowan Sand occurs, than outside them.

The source of the Lowan Sand has been variously attributed. Crocker (1946) concluded that what is here termed the Lowan Sand is the re-sorted quartzose A horizon of former dunes of the Bridgewater Formation stripped by wind during an arid period. Sprigg (1952, 1959) found a progressive decrease northward in the lime concentration and a complementary increase in the quartz content of the dunes of the Bridgewater Formation. He suggests that the sand has been winnowed from the Bridgewater Formation and has migrated eastward under the influence of strong winds. However, reconnaissance mapping of the Lowan Sand has not revealed significant regional variation of grain size or shape (confirmed by Blackburn pers. comm.) that would support Crocker's and Sprigg's suggestion for the origin of the Lowan Sand.

Hills (1939) was of the opinion that the Lowan Sand is the erosive product of the Diapur Sandstone. This conclusion is substantiated by the similarity of the Lowan Sand, texturally and mineralogically, to the Diapur Sandstone. Furthermore, the Lowan Sand is always closely associated with the Diapur Sandstone both within and outside the 'Deserts'.

The age of the Lowan Sand is considered to cover most of the Quaternary period. It is considered that during Quaternary times, climatic conditions become conducive to the breakdown of the Diapur Sandstone, and that this process, combined with migration of the dunes, has continued to the present.

The Lowan Sand, as defined here, does not include all outcropping loose sand in the Murray Basin, for there is frequently sand at the crests of the E.-W. dune chains that, in fact, belongs to the Piangil Member of the Woorinen Formation.

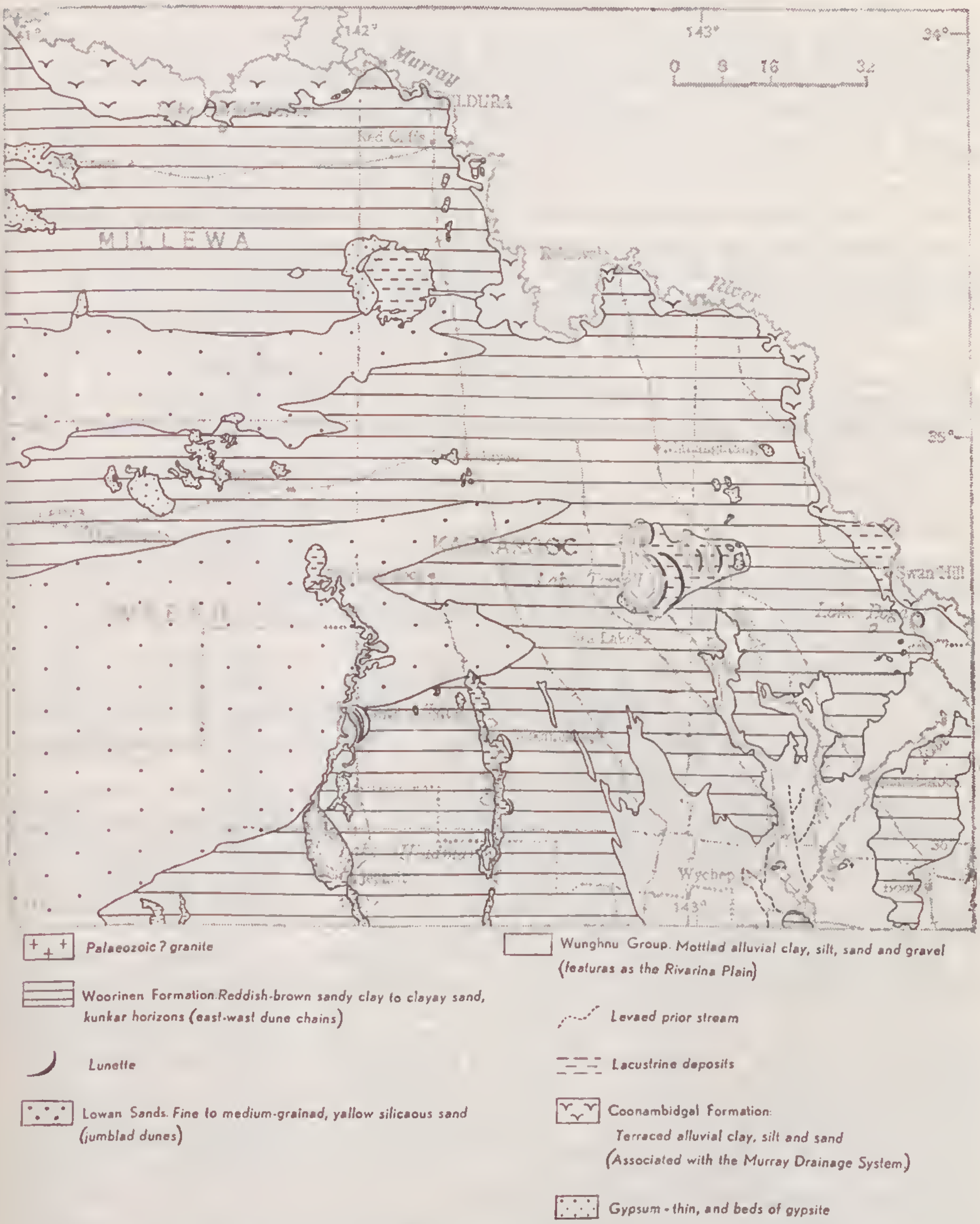

FIG. 8—Distribution of Quaternary rock-units in the Mallee Region.

WOORINEN FORMATION—

The aeolian landscape W. of the Riverine Plain, except for the Lowan Sand, consists of pale to dark reddish-brown, calcareous sandy clay and clayey sand in which at least five superimposed soils are present. The name proposed for these sediments is the Woorinen Formation, named after the township of Woorinen W. of Swan Hill; a low E.-W. trending dune in the N. part of allotment 8, section B, parish of Tyntynder is selected as the type locality; the choice is based on stratigraphic work by Churchward (1960). At this locality, hand-drilling into the dune has shown that the Woorinen Formation persists for more than 20 ft. Soil development on each aeolian layer leaves only thin zones of unweathered Woorinen Formation. In the Woorinen district, the unaltered zones are usually less than 2 ft thick; the shallowest of these lies at a depth of 4 to 5 ft. The unaltered material consists of calcareous sandy clay resting disconformably on earlier soils.

The upper surface of the Woorinen Formation is moulded by wind into various forms; the most widespread and characteristic of these are the E.-W. dune chains which consist of aligned unit dunes, typically several hundred feet wide, 10 to 50 chains long, and 10 to 30 ft high. In profile they are asymmetrical, with the S. slope steeper than the N. slope. The distance between dune chains generally ranges from 10 to 80 chains.

Although the dune chains almost certainly formed parallel to, rather than transverse to the dominant wind directions, they cannot be classed as typical longitudinal dunes. They are close, in fact, to Bagnold's (1960) 'tear-drop' longitudinal dune chains, which he thought to be due to winds shifting in direction by more than 90°. The dunes in the Mallee Region have formed under the influence of winds with a westerly vector; under the present wind regimen the dunes of Lowan Sand are moving eastward.

The shape and frequency of the dune chains in the Mallee Region are variable. In the far NW. the dunes are prominent and separated by narrow swales, but to the SW. the dunes are much more subdued in form and are separated by broad swales. E.g., in the Waitchie-Ultima district the dunes are low, elliptical to circular hummocks; near Brim the Woorinen Formation is a featureless sheet.

Throughout much of its distribution within the Mallee Region, the Woorinen Formation rests disconformably on the Blanchetown Clay or Bungunnia Limestone; where these are missing it rests disconformably on the 'lateritized' surface of the Diapur Sandstone. The topography is a composite of the closely spaced parallel E.-W. Woorinen Formation dune chains and the more irregularly spaced NNW.-SSE.-trending ridges of the buried Diapur Sandstone.

Churchward (1960, 1961a, 1961b, 1963a, 1963b), on pedological criteria, provided a rational means of differentiation of the Woorinen Formation into members. Hills (1939) had previously suggested that the lime rich bands in the dunes represented illuvial soil horizons and that the intervening layers of relatively non-calcareous, siliceous material were eluviated horizons. He further postulated that a series of arid periods contributed to dune formation and that these periods alternated with those of more humid conditions during which soils were developed. This interpretation has been endorsed by Butler (1956, 1958, 1959), and later by Churchward (1960, 1961a, 1961b, 1963a, 1963b) who has recognized five superposed aeolian accumulations disconformable to one another in the E.-W. dunes to the NW. of Swan Hill. Churchward named these aeolian layers, in order of increasing age; the Piangil, Kyalite, Speewa, Bymue, and Tooleybuc layers. These layers are referred to in this paper as formal members of the Woorinen Formation. Churchward's names have been adopted for these members except for the Tooleybuc layer;

this is here termed the Miralie Member because the name 'Tooleybuc' has been used already for a stratigraphic unit elsewhere in Australia.

Each of the members of the Woorinen Formation is parallel or sub-parallel to the ground surface. The crest of any member is characteristically displaced to the east and south of the crest of the next oldest member. This skewed relationship of members within a dune is most pronounced in the W. part of the Mallee Region where erosional truncation of one or several members, especially on the N. and W. slopes of dunes, has exposed the limey B horizons, variously known as calcrete, kunkar, caliche, or travertine.

MIRALIE MEMBER—

Named after the township of Miralie in N. Victoria, the Miralie Member is synonymous with the Tooleybuc layer of Churchward (loc. cit.), a name pre-occupied for stratigraphic use. It appears to be derived from similar parent material to the younger members, but is more deeply weathered.

BYMUE MEMBER—

The Bymue Member is a weathered calcareous, clayey-sand stratum buried disconformably below the Speewa Member. It is named after the parish of Bymue in New South Wales; it occurs typically at the crest of an E.-W. dune, 8 miles NE. of Tooleybuc Village (N.S.W.) where it is buried disconformably beneath the 22-in. thick Kyalite Member, no Speewa Member being present there.

SPEEWA MEMBER—

The Speewa Member is a calcareous clayey sand, named after the township of Speewa, N.S.W., where it occurs at the type locality of the Kyalite Member, but buried beneath it in the same dune; it outcrops in the swales adjacent to this dune. Where it is weathered, mobilization of the calcareous and clayey constituents by pedogenic processes has caused marked profile differentiation. It is known from field observations to contain a larger proportion of sand in the far NW. part of the Mallee Region than in the SE. part. Churchward (1963a) demonstrated that the Speewa Member in the swales NW. of Swan Hill is bimodal with maxima coinciding with very fine-grained sand and medium-grained sand, whereas at the crests of the dunes it is unimodal, being mainly coarse-grained sand. Unlike the younger Piangil and Kyalite Members, the Speewa Member persists across the swales, where it usually outcrops. It also outcrops in the SE. part of the Mallee Region where the Woorinen Formation has a hummocky form.

The thickness of the Speewa Member varies; it is thickest on the E. and S. slopes of dunes and hummocks where it may be 10 ft thick; it is thinnest on N. and W. slopes exposed to wind erosion. Often on N. and W. slopes of E.-W. dunes, particularly in far NW. Victoria, erosion has exposed the lime-enriched B horizon.

Soil development on the Speewa Member is considerable; the degree of soil development varies, being greatest in the far NW. part of the State. The variation in soil development is thought to have been mainly influenced by the permeability of the Speewa Member; this is higher in the W. part of the Mallee Region, where it becomes coarser-grained. Churchward (1963b) indicates that for the Swan Hill district, lime has been leached from at least the top 14 in.; the clay maximum there is at a depth of more than 9 in. and is associated with pedal development.

The Kyalite Member, named after the Kyalite (Edward) R. in New South Wales, is a brownish to reddish-brown, sometimes greyish brown, calcareous clayey

KYALITE MEMBER—

sand forming an asymmetric eapping to the E.-W. dunes and associated hummoeks. Its type locality occurs on an E.-W. dune near the S. boundaries of allotments 33, 34, 35, and 36, parish of Tyntynder. The Kyalite Member diseonformably underlies the Piangil sand; it rests disconformably on the weathered Speewa Member, except where erosion has truneated this member. The thiekness of the Kyalite Member varies; in railway and road cuttings in the Victorian portion of the Murray Basin it is seen to be usually 1 to 13 ft thick, but Churchward (1963a) found in the Woorinen district that it ranged up to 5 ft thiek and was thickest on the S. and the E. slopes of dunes.

Insuffieient meehanical analyses of the Kyalite Member prevent eomment on regional textural trends, but within eaeh dune profile of the member there is a eharacteristic pattern in grain size. In the dunes to the NW. of Swan Hill, e.g. the median grain size grades from very fine sand in the swales up to medium-grained sand at the crest of the dunes (Churchward 1963a).

The differentiation of the soil profile is only slight; lime has been leached from the top few inehes, the clay maximum is at a depth of about 3 in., and there is no pedal development (Churchward loe. eit.). The Kyalite Member, unlike older members, is relatively homogencous, owing to this limited soil development; lime eement binds the member togther. The lime occurs as hollow tubules, pseudomorphie after roots and rootlets, which have since deeayed.

Piangil Member—

The Piangil Member, named after the township of Piangil, is the youngest member, and consists of loose yellowish-orange sand. Its type loeality is at the crest of an E.-W. dune, 1 mile NW. of Piangil township in allotment 142, parish of Piangil. It oceurs typically at the crests of dunes and has built up against sueh obstacles as vegetation, fences, and buildings. Due to truneation by erosion it probably rests on all members of the Woorinen Formation, though it most commonly rests on the Kyalite Member. It is typieally less than 5 ft in thickness but probably exeeeds 40 ft in plaees. It shows no soil development, but primary structures ineluding eross-bedding are present.

Soil Development on Members of the Woorinen Formation

The members of the Woorinen Formation are similar in lithology and form; their reeognition requires knowledge of their vertical relationships to other members and, most important, their degree of soil differentiation. The diseussion below refers to the far E. part of the Mallee Region where the Woorinen Formation is more clayey than elsewhere. Here, Churehward (1960, 1961, 1963a, 1963b, 1963c) has deseribed both outcropping and buried soils in detail; the following remarks are largely a synthesis of his work.

Soil profiles are developed on all members exeept the Piangil Member, obliterating depositional bedding and texture. Several trends of profile differentiation have oceurred to varying degrees. The ealcite, which was originally dispersed throughout each member, has been mobilized and leached down the profile to give a lime pan or coneretionary caleite horizon of kunkar; the oldest horizons, naturally enough, have been most affeeted by this process. Clay mobilization and soil structure development follow the same trend.

Beeause the degree of soil development increases directly with the age of the member in whieh it is developed, Churehward (1963b) concluded that the relative durations of the soil-forming periods were Miralie > Bymue > Speewa > Kyalite. Other factors, however, have influeneed soil differentiation. Beeause of the thinness of members, weathering may be a cumulative process whereby there is continued mobilization of elements and re-organization of structure of buried members owing to the movement through them of groundwater.

Correlation of the aeolian sequences of the Mallee Region with the Quaternary time scale requires several assumptions. Firstly, it is assumed that the Quaternary climatic cycles of the Northern and Southern Hemispheres were in phase. It is further assumed that these cycles have some expression in the regional stratigraphy; this influence has been the subject of controversy. The lime present in the Woorinen Formation is considered by Crocker (1946) to have been wind winnowed from the calcareous aeolianitic Bridgewater Formation under the influence of strong westerly winds. If the genetic relationship between the Bridgewater Formation and the Woorinen Formation is correct, then dating of the Bridgewater Formation would enable dating of the Woorinen Formation; but this genetic relationship remains to be proved. Some workers are of the opinion that the stranded coastal dunes of the Bridgewater Formation formed during interglacials, whereas others consider them to have formed during glacials.

Butler (1956) has applied the lithogenetic term 'parna' to aeolian clay present in the Widgelli Member in the Riverine Plains to distinguish it from loess, which in the strict sense must be regarded as silt-sized wind-blown material. The parna is considered to be derived by deflation of soils during the unstable phase of the K cycle of Butler (1959); these unstable phases alternated with stable phases during which soils were developed, the stable phase being correlated with humid conditions and the unstable phase with arid conditions. Movement of dust continues to act to a minor degree at the present time, having been accelerated by human activity. It is associated with strong turbulent wind flowing over the drier regions of inland Australia, with duststorms more prevalent during dry than wet years (Loewe 1943).

Perhaps the most feasible hypothesis concerning the Quaternary climates is that of migrating climatic belts. It is generally assumed (Keble 1947, Fairbridge & Teichert 1952) that during the glacial phases climatic belts migrated equatorwards, bringing temperate and wet (pluvial) conditions to lower latitudes.

Sprigg (1959, 1964) claims that the coastal dune system fossilized the low sea level coasts of the glacial phases and that, at this time, 'loessial lime' was carried inland and lunettes formed. He believes that, although the conditions were wetter during the glacial phases, the winds were stronger and came from the west. This, he claims, would account for the position of lunettes, their relation to lakes and the trend of E.-W. dunes. It is my opinion that these aeolian features could equally have been formed under a wind regimen identical with that presently operating.

Lunettes

Lunettes, or crescent-shaped dunes, border the E. side of existing lakes and ancestral lakes. In plan they are concave to the west; their height decreases from the centre towards their N. and S. ends; their windward slope (lake side) is usually steeper than the lee slope. Lunettes in the Mallee Region range in height from a few feet up to 100 ft, and in length from a few chains to about 15 miles. There may be only one lunette adjacent to a lake, e.g. alongside the ancestral lake at Pine Plains, or there may be a series of lunettes, e.g. alongside L. Albacutya where four lunettes are probably present. Where there is a series of lunettes they are generally sub-parallel with their radii converging to a common point. Lunettes up to 15 miles E. of the present E. shore of L. Tyrrell are interpreted as lunettes of a huge ancestral L. Tyrrell. L. Timboram and L. Walpole, and their associated gypsum flats, are accordingly regarded as relict lakes occupying depressions between lunettes of the ancestral L. Tyrrell.

The lunettes consist of clay, silt, and sand; gypsum or calcium carbonate horizons may be present. The lunettes alongside L. Albacutya consist of sand, whereas those in the Kerang district consist of clay and fine-grained sand (Baldwin, Burvill, & Freedman 1939). Mature soils are developed on some of the main lunettes and in some, especially near the S. and N. ends of lakes, buried soils are present.

Contradictory explanations for the genesis of lunettes have been presented. Hills (1939, 1940) considers that, when the lake was full, atmospheric dust of regional origin was captured by spray droplets derived from the lake; this dust dropped to form the lunette. By contrast, Stephens & Crocker (1946) consider that lunettes are derived from material blown from the dry floor of the lake. In support of the 'full lake' theory, Hills (1939) reasons that it would be improbable for aeolian surface drift and saltation to produce the regular form of the lunette and further, that the material of the lake floor is so fine-grained that when the lake is dry, much of it would undoubtedly be lifted into the air by strong winds and carried to remote areas.

A cogent refutation of the 'full lake' theory for genesis of lunettes is presented by Stephens & Crocker (1946), who maintain that the sand of which some lunettes are composed is too coarse to be moved by saltation and probably was moved by surface creep. They also remark that clay dust is not composed of ultimate particles, but of aggregates which behave like sand grains in being transported by saltation and surface drift. Indeed, I have found that lunettes may contain laminated aggregates similar to the dry clay aggregates found on the lake floors. The presence of gypsite in these lunettes alongside the gypsum flats is regarded as additional evidence for lunette material being derived mainly from the depression's floor. In the L. Boga district there are very low lunettes alongside areas not covered by water but where the water-table is sufficiently shallow to lie within the capillary fringe. Under these conditions, salts may well have precipitated at the surface causing thinning of the vegetation, and thus allowing westerly winds to carry salts and clay aggregates eastward to build up a lunette.

Multiple lunettes are explained by recession of the old shore line; each lunette formed individually, the oldest being farthest from the lake and the youngest being the closest. Lake recession would be followed by encroachment of vegetation, which would help trap the moving material, thereby enhancing the rate of accumulation.

The stratigraphy of the lunettes is known only in a general way. Probably most prominent lunettes in the Mallee Region pre-date the earliest phases of the Coonambidgal Formation. This is shown for instance at Swan Hill where the ancestral Loddon evades a large lunette to flow around its S. end. Paleosols within lunettes are expected to provide the best means of correlating the stratigraphy of the lunettes with that of the Woorinen Formation, but at present the relation between the periods of lunette building and the development of the E.-W. dunes is not known. It is obvious, however, that the lunettes formed when the winds were dominantly westerly. Sprigg (1959) claims that the lunettes were deposited during humid phases when the winds were dominantly westerlies due to equatorwards migration of the anticyclonic belt. Climatic fluctuations, nevertheless, may have had little effect on lunette formation; the arrangement of multiple lunettes, for instance, suggests a progressive decrease in lake size with the climate becoming progressively drier since lunette formation began.

Quaternary Alluvial Deposits

Blanchetown Clay and Bungunnia Limestone—

Both the Blanchetown Clay and Bungunnia Limestone, defined by Firman (1965), are Pleistocene lacustrine deposits found in association with one another, and limited to the NW. part of the Mallee Region and adjacent South Australia on the downthrow side of the Murrayville monocline; they occur between the ridges of Diapur Sandstone, but not on them.

The Blanchetown Clay is a light grey to weak red clay to clayey sand in which crustacean fragments are rarely found. It rests disconformably on either the Diapur Sandstone or a lower unit of the Lowan Sand. Although usually less than 20 ft thick, it ranges up to a maximum thickness of 60 ft in the banks of the Murray R. at Red Cliffs. Resting conformably on the Blanchetown Clay is the less widespread, thin, bedded, dolomitic Bungunnia Limestone; carapaces of the ostracode *Cypris praenuncius* (identified Chapman 1936) and algal structures are common. The Bungunnia Limestone is overlain by part at least of the Woorinen Formation.

Wunghnu Group

The alluvial sediments found in the Mallee Region and widespread in the Wycheproof-Teddywaddy district were discussed earlier under the Tertiary part of the Wunghnu Group. This discussion was concerned with the broader aspects of subsurface data. The following discussion concentrates on the younger, and generally outcropping, Quaternary units of the Wunghnu Group.

Shepparton Formation—

The Shepparton Formation is proposed for those essentially alluvial sediments of the Murray Basin that are older than the Coonambidgal Formation; it forms part of the Wunghnu Group.

Named after the city of Shepparton, the Shepparton Formation is typically exposed nearby in the E. bank of the Goulburn R. near the S. boundary of allotment 59, parish of Kialla, where it is represented by over 30 ft of fine-grained alluvial sediments marked at the top by a soil overlain by the thin and discontinuous Widgelli Member. The sequence of fine-grained sediments is broken by two further paleosols, enabling a further subdivision into members: Kialla Member, Katandra Member, and Quiamong Member. The youngest member of the formation, the Mayrung Member, is absent from this section.

In Victoria, the Shepparton Formation is limited to the Northern Plains and the alluvial valleys of N.-flowing streams in the Central Highlands. It is rare in the E.-W. dune system, where it is invariably buried. The geomorphology of the Northern Plains is a reflection of the upper surface of the Shepparton Formation, which is in places buried beneath a veneer of a sixth member of this unit, the aeolian Widgelli Member.

The best known members of the Shepparton Formation are its shallowest and youngest members, the Quiamong and Mayrung Members; these deposits and facies variations have been described by Butler (1958). Older members are assumed to have been derived from similar streams despite the absence of known levee deposits associated with them. The prior stream deposits consist mainly of clays and silty clays, but there are also sands and rare gravels. The sands may extend through the whole vertical section of the prior stream deposits, or they may occur as a thin extensive sheet at their base, grading upward into finer material.

These prior stream deposits doubtless had a similar provenance to the Recent deposits of existing streams, the former and present drainage regimes having essentially the same catchments on fine-grained Palaeozoic sediments, metasediments and granites of the Central Highlands, blanketed in places by late Pliocene and Pleistocene basalt flows.

Like the existing streams, the prior streams, at least in their final and aggrading phase, displayed high sinuosity. Occasionally, the point bar pattern is visible at the surface, demonstrating that lateral migration of the stream helped to build up the deposits; but in general, overbank deposition seems to have been the most significant type of deposition, usually extending for several miles from the prior stream course in the cases of the observable Mayrung and Quimong Members, and obliterating the point bar pattern.

COONAMBIDGAL FORMATION—

The 'Coonambidgal', defined by Butler (1958), is here used for the first time as a formal formation name. Its type locality is outside the Mallee Region in the bank of the Coonambidgal Ck, near the NE. corner of lot 75, parish of Deniliquin, New South Wales. It is applied to the deposits of existing streams, or their recent ancestors, in the Murray Basin. It is clearly mappable as a floodplain with paired terraces alongside existing streams, some of whose dimensions are out of harmony with their present discharges. In the Mallee Region, incised streams have deposited these terraces below the level of the Woorinen Formation; the width of these terraces reaches several miles in the case of many cross-sections of the Murray R. The terrace surfaces frequently display scrolls and oxbow lakes, remnants of earlier meandering.

The Coonambidgal Formation is generally a slightly micaceous silty clay, but also includes clay, silt, sand, and gravel, either alone or as various admixtures; it is generally less than 60 ft thick. The degree of profile differentiation in soils of the Coonambidgal Formation is less than that occurring in soils of the Shepparton Formation. There are variations in soil type throughout the formation caused by variation in parent material and microtopography. Baldwin, Burvill, & Freedman (1939) described soils in the Kerang district which Pels (1964) later associated with an ancestral Coonambidgal Formation river channel along which Pyramid Ck now flows.

The Coonambidgal Formation is best known where it is associated with the Murray drainage system (Pels 1964). The existing Murray R. follows a relatively new course to Wakool Junction, but beyond this point it follows the course of the ancestral Murray R.; the present Wakool R. is an ancestral course of the Murray R. The Murray R., downstream from Wakool Junction, adopts the same meander pattern and channel width as the Wakool R.; immediately upstream from the junction it has a wavelength of about 15 chains, whereas downstream from the junction its wavelength is about 50 chains; downstream from the junction the Murray R. occupies a gorge incised into the Woorinen Formation and the underlying units. The alluvial deposits of this tract consist of two inset terraces and a narrow floodplain. Upstream from Wakool Junction the three Upper Pleistocene to Recent phases of activity of the Murray R. are not preserved in the one valley, but have been separated due to recurrent tectonic movement (Pels 1964) on the Cadell Fault (Harris 1938). Between Wentworth and the NW. corner of the State there is a huge terraced area of alluvial plains (terrace No. 2); this terrace will be drowned following construction of the Chowilla Dam in South Australia.

The sequence of terraces within the Coonambidgal Formation suggests periodic variation in discharge in response to climatic change. The above scheme implies three phases of degradation alternating with periods of aggradation, coinciding with variations in discharge during Upper Pleistocene to Recent times. Alternatively, there may be only two main phases represented by a floodplain (= terrace No. 1 + floodplain) and a major terrace.

The ancestral streams involved in the deposition of the Coonambidgal Formation are likened to the existing river courses (excluding anabranches). These streams are characterized by high sinuosity (in excess of 2), a high depth to width ratio, and approximately 45° banks. Taking the plain tract of the Murray R. as an example: its sinuosity is generally over 2, its depth to width ratio varies from 1 : 18 at Albury to 1 : 28 at Mildura; its bed slopes 9 in. per mile at Albury, decreasing to 3·8 in. per mile near the South Australian-Victorian border. The high depth to width ratio is explained by the inherent resistance of the clayey banks to scour, and the stabilizing effect of vegetation, principally redgum—*Eucalyptus camaldulensis*.

Evaporites

Recent evaporites are common in the Mallee Region but rarer away from it. The precipitation of evaporites is understandable as the average annual evaporation of 50 to 60 in. greatly exceeds the annual average rainfall of 10 to 14 in.; this achieves a main prerequisite, viz. potential loss of water by evaporation exceeding the rainfall; the process is further aided by movement of surface water and groundwater into the area.

Evaporites in the Mallee Region consist of calcium carbonate, halite, and gypsum. Except that some calcium carbonate can be present with earthy gypsum, each of these salts is usually found in geomorphically distinct situations:

(a) Calcium carbonate is concentrated in the paired levees of the prior streams of the Wycheproof-Towaninny district. It is thought to have been precipitated from stream water lost by influent seepage and is attributed partly to evaporation of capillary waters within the levees.

(b) Halite is precipitated in shallow lakes or salinas. These lakes may be fed by—

  (i) the internal surface drainage, e.g. L. Tyrrell and L. Timboram, respectively the terminal lakes of the Tyrrell and Lalbert Creeks, both effluents of the Avoca R., or

  (ii) almost entirely by groundwater, e.g. the Pink Lakes N. of Underbool, and L. Kunat near Swan Hill.

The salinas are occupied by saline water during most, if not all, of the year; wave action is responsible for a well-defined shore-line. Another conspicuous feature of the salinas is a lunette of sand or clay, or an admixture of both, situated along the eastern margin of the lake. Analyses of water from a number of salinas show a high amount of sodium and chloride, probably from cyclic salts, with lesser amount of magnesium, calcium, and sulphate. As the water evaporates, halite is precipitated almost exclusively, apart from minor amounts of calcium carbonate and gypsum. Cane (1962) has demonstrated for the Pink Lakes that the seasonal fluctuation of water level assists in draining away the magnesium-rich bitterns remaining after the halite has precipitated; this mechanism is believed to apply to the other salinas as well.

(c) Gypsum occurs in thin but extensive sheets or gypsum flats, believed to be the sites of ancestral lakes. There is generally only one gypsum bed beneath these flats, often extending from a depth of about 1 to 4 ft, but in the Cowangie district gypsum is found at depths as great as 20 ft, with several gypsum beds separated by sandy clay. The largest gypsum flats occur south of Meringur, at Nypo, at Raak Plain W. of Hattah and Nowingi, and at Kow Plain near Cowangie (Fig. 8). They are characteristically marked by an expanse of dry grey mud covered by an efflorescence of evaporite salts and a growth of samphire—*Crithmum maritimum*. Low winding dunes composed of gypsite, variously known as earthy gypsum, flour gypsum, copi, or kopi, are sometimes present on the flats.

A section typical of a gypsum flat is shown by a bore sunk in allotment 8, Parish of Tutye:

	ft
Grey mud (possible clay-sized gypsum) and gypsite	0 — ½
Gypsite, white	½ — 6
Gypsite and selenite	6 — 10
Sandy clay, yellow	10

Water is unknown at the surface of the gypsum flats, except temporarily as a result of heavy rain; instead, the water-table lies several feet below the surface. The gypsum is a chemical precipitate from saline groundwater. The water apparently rises due to capillary action precipitating the gypsum as coatings on existing crystals in the zone of aeration. During this process, which probably has continued for thousands of years, co-precipitation is slight and restricted to sodium chloride and calcium carbonate. An important key to the genesis of gypsum and salt is that, in those depressions in gypsum flats in which the water-table is intersected, salt is the major precipitate. This demonstrates that where water is exposed and entirely or almost entirely evaporated, sodium chloride predominates, but where the water-table is just below the surface there is fractional crystallization of calcium carbonate and gypsum with the other salts remaining in solution.

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Explanation of Plates

PLATE 53

Fig. 1—Exposures of Woorinen Formation derivatives, Bungunnia Limestone, Blanchetown Clay, and Diapur Sandstone along the cliffs of the Murray R. at Boundary Point, far NW. Victoria.
Fig. 2—Section through an E.-W. sand dune of the Woorinen Formation in a cutting of the Calder Highway at Hattah.
Fig. 3—Typical gypsum flat ('copi swamp') near Nowingi.
Fig. 4—Sand dune of the Lowan Sand, Big Desert.

PLATE 54

Vertical aerial photomosaic of the jumbled dune pattern of the Lowan Sand, adjoining the E.-W. dune system of the Woorinen Formation to the north and lacustrine deposits to the south (Wirrengren Plain) in the Big Desert, S. of Underbool. Scale—1 inch : 1 mile.

Plate 55

Vertical aerial photomosaic of the gypsite deposits of the Raak Plain, and associated lacustrine and aeolian deposits, SW. of Nowingi. Scale as for Pl. 54.

Plate 56

Vertical aerial photomosaic of the Coonambidgal Formation floodplain and terrace deposits associated with the Murray R., E. of Nowingi. Scale as for Pl. 54.

Addendum

While this paper was in press and just prior to receiving proofs, a geological map of the Pinnaroo-Karoonda area by J. B. Firman was published by the South Australian Geological Survey. Some rock units used there are equivalents of units used in the above text. The geological section accompanying the map lends further support to the synonymy of the Ettrick Formation with the Netherby Marl; the Parilla Sand is equivalent to the Diapur Sandstone; the Molineaux Sand corresponds to my use of the Lowan Sand plus the Piangil Member of the Woorinen Formation.